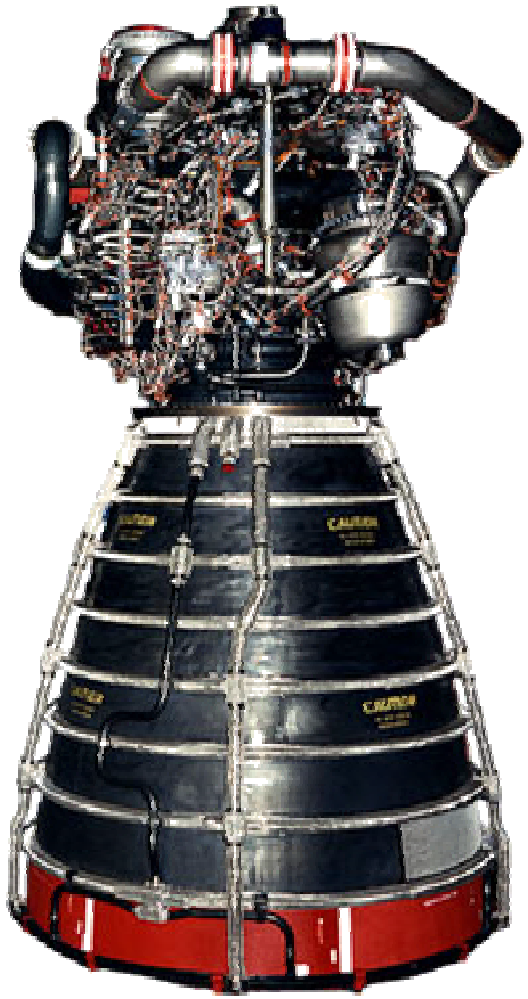


Discovery STS-114

Space Shuttle Program

SSME Flight Readiness Review

June 29-30, 2005

Discovery STS-114

Agenda

- Major Components
- SSME Return to Flight Configuration / First Flight ECPs
- Engine Performance
- Special Topics
  - HPOTP Knife Edge Seal Cracking
  - Nozzle 5007 Tube Ruptures
- Material Review & Software System Notes Reassessment
- SSME Hazards Status
- CoFR Exceptions and Readiness Statement

Discovery STS-114

SSME Major Components

Engine	ME-1 / 2057 *Block II*	ME-2 / 2054 *Block II*	ME-3 / 2056 *Block II*
Last Hot-Fire	**902-837**	**902-844**	**902-845**
Powerhead	6011	2036	6012
Main Injector	6009	6010	2036
MCC	6025	6026	6004
Nozzle	2033	5005	2030
Controller	F53 (1)	F57 (1)	F59 (1)
HPFTP	8029R1	8033R1	8030 (1)
LPFTP	4208	2136R1	6106R1
HPOTP	8116 (1)	8126 (1)	8112
LPOTP	6006	2234	2232

(1) Changes after last hot-fire.

Discovery STS-114

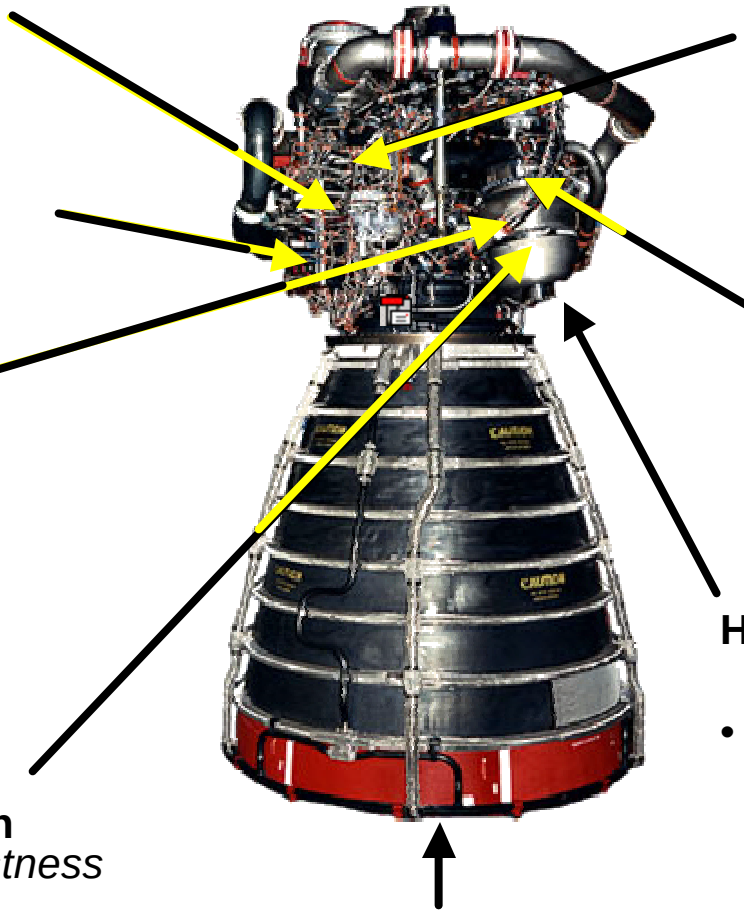
SSME Return to Flight Configuration / First Flight ECPs

Main Fuel Valve (MFV) End Cap
- *Eliminated Leakage and Improved Safety*

New Baseline Software
- *Increased Reliability and Supportability*

HPFTP Liquid Nitrogen Insulation
- *Increased Effectiveness in Prevention of Liquid Nitrogen Formation*

HPFTP -712 Configuration
- *Increased Life and Robustness*



HPOTP Upgrades
- *Reduced Maintenance*
- *Increased Margin*

Main Injector Solid Fuel Sleeves
- *Increased Margin against LOX Post Tip and Face Plate Erosion (E2054 only)*

HPFTP Two Piece Speed Sensor & Retaining Bolts
- *Increased Reliability*

Nozzle Ablative Redesign
- *Increased Life*

Discovery STS-114

Predicted SSME Ignition Confirm Margins

Parameter	Margin Sigma		
	ME-1 (2057)	ME-2 (2054)	ME-3 (2056)
HPFTP Minimum Speed	3.9	4.8	6.2
Min/Max Ignition Pc	3.5	4.6	5.6
Antiflood Valve Min Open	26.0	25.0	22.3
HPFTP Max Turbine Temp	3.4	3.5	4.4
HPOTP Max Turbine Temp	4.6	5.8	5.3
HPOTP Min Turbine Temp	8.9	8.1	5.3
Preburner Max Purge Pressure	29.1	29.4	28.5
POGO GOX Min/Max Pressure	3.1	3.5	3.2

Discovery STS-114

Predicted SSME Performance at 104.5% P.L.

At Engine Start + 200 seconds

Parameter	ME-1 (2057) Sigma	ME-2 (2054) Sigma	ME-3 (2056) Sigma
HPFT Disch Temp A, Deg R	1.8	c **[2.1]**	0.7
HPFT Disch Temp B, Deg R	a **[2.3]**	-0.8	-1.1
HPOT Disch Temp A, Deg R	-0.4	-0.1	0.6
HPOT Disch Temp B, Deg R	-0.3	-0.2	0.6
HEX Interface Temp, Deg R	-0.5	-0.7	0.5
HPFTP Speed, rpm	0.6	-0.1	-0.1
LPFTP Speed, rpm	-0.7	1.3	-1.1
HPOTP Speed, rpm	-0.6	-0.2	-0.8
LPOTP Speed, rpm	-0.1	0.3	-0.4
OPOV Position, %	0.1	d **[-2.5]**	0.8
FPOV Position, %	b **[3.7]**	d **[-2.3]**	-1.8
PBP Disch Pressure, psia	0.6	1.7	0.8
HPFTP Disch Pressure, psia	0.6	-0.6	-0.3
HPOTP Disch Pressure, psia	1.5	-0.4	1.1
HPFTP U/N	8029R1	8033R1	* 8030
LPFTP U/N	4208	2136R1	6106R1
HPOTP U/N	* 8116	* 8126	8112
LPOTP U/N	6006	2234	2232

[] Exceeds database two sigma
* Change from last flight / acceptance test

a Low HPFTP performance
b Stackup of hardware effects
c Low HPFTP performance and high inter-channel delta
d High performing preburner pump

Discovery STS-114

Predicted Redline Margins at 104.5% P.L.

Parameter	Margin Sigma		
	ME-1	ME-2	ME-3
HPFT Discharge Temp ChA, Deg R HPFT Discharge Temp ChB, Deg R	5.2 4.7	5.0 7.4	6.2 7.7
HPOT Discharge Temp ChA, Deg R HPOT Discharge Temp ChB, Deg R	7.7 8.9	7.5 8.8	7.0 8.2
HPOT Discharge Temp ChA, Deg R HPOT Discharge Temp ChB, Deg R	6.2 7.0	6.4 7.2	7.1 7.8
HPOTP IMSL Purge Pr, psia	4.2	6.0	5.4
Low MCC Pc, psid Command-ChA Avg Command-ChB Avg	 22.0 25.3	 22.7 26.1	 22.0 25.4

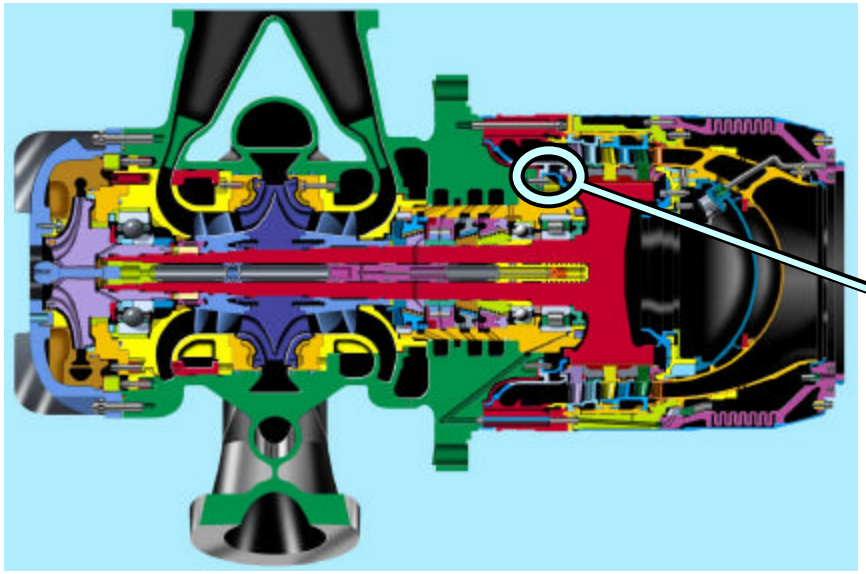
HPOTP Knife Edge Seal

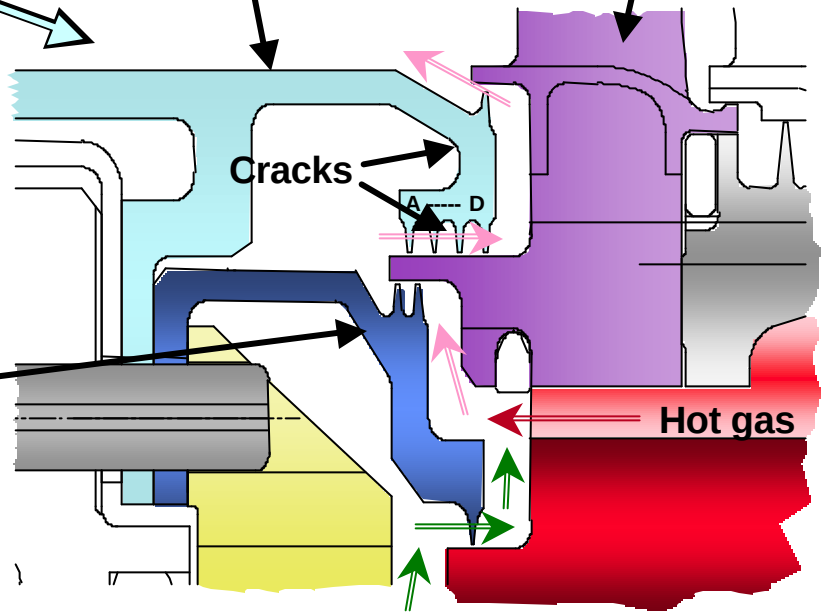
Outboard Seal (-011) Cracking

- **Issue**
  - Cracking of Turbine Outlet Duct Seal creates FOD concerns to downstream components
- **Background**
  - Multiple seals found with radial cracks in 4-tooth seal during overhaul and recycle operations
    - 3 flight configuration seals
      - Severity varies from single crack in one tooth to multiple cracks in all four teeth
    - 2 non-flight, early development configuration seals
      - Multiple cracks in all four teeth
  - Single occurrence of circumferential web cracking
    - Intermittent, 360 degrees, one location with through crack
  - Cracking had no impact on seal functionality or engine operation
  - No FOD generated

HPOTP Knife Edge Seal

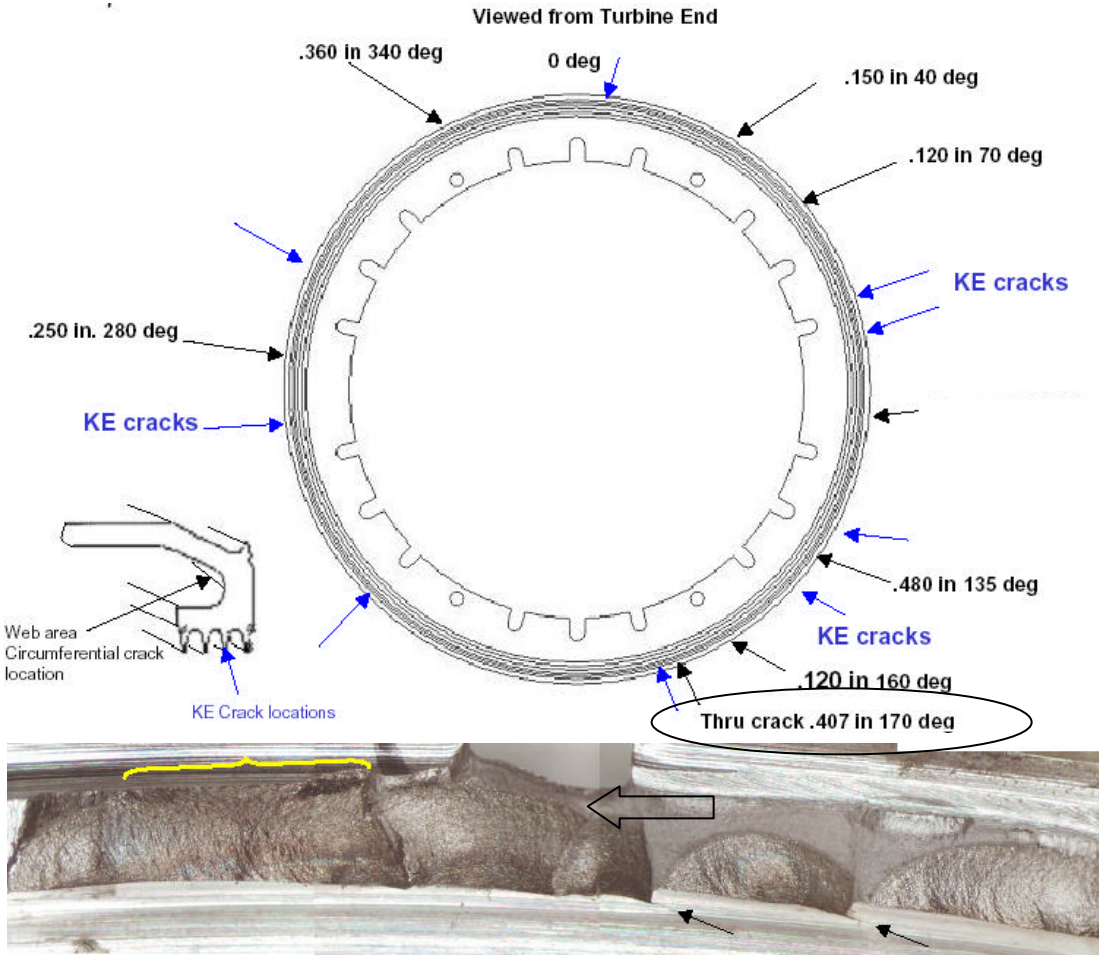
Outboard Seal (-011) Cracking

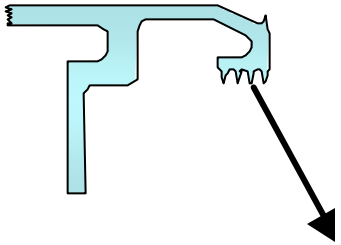


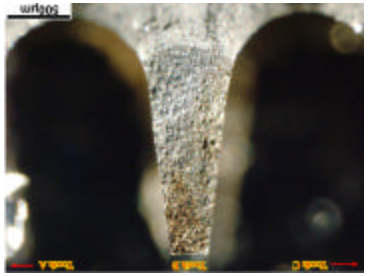


HPOTP Knife Edge Seal

HPOTP 8016R4 Outboard Seal (-011) Crack Indications





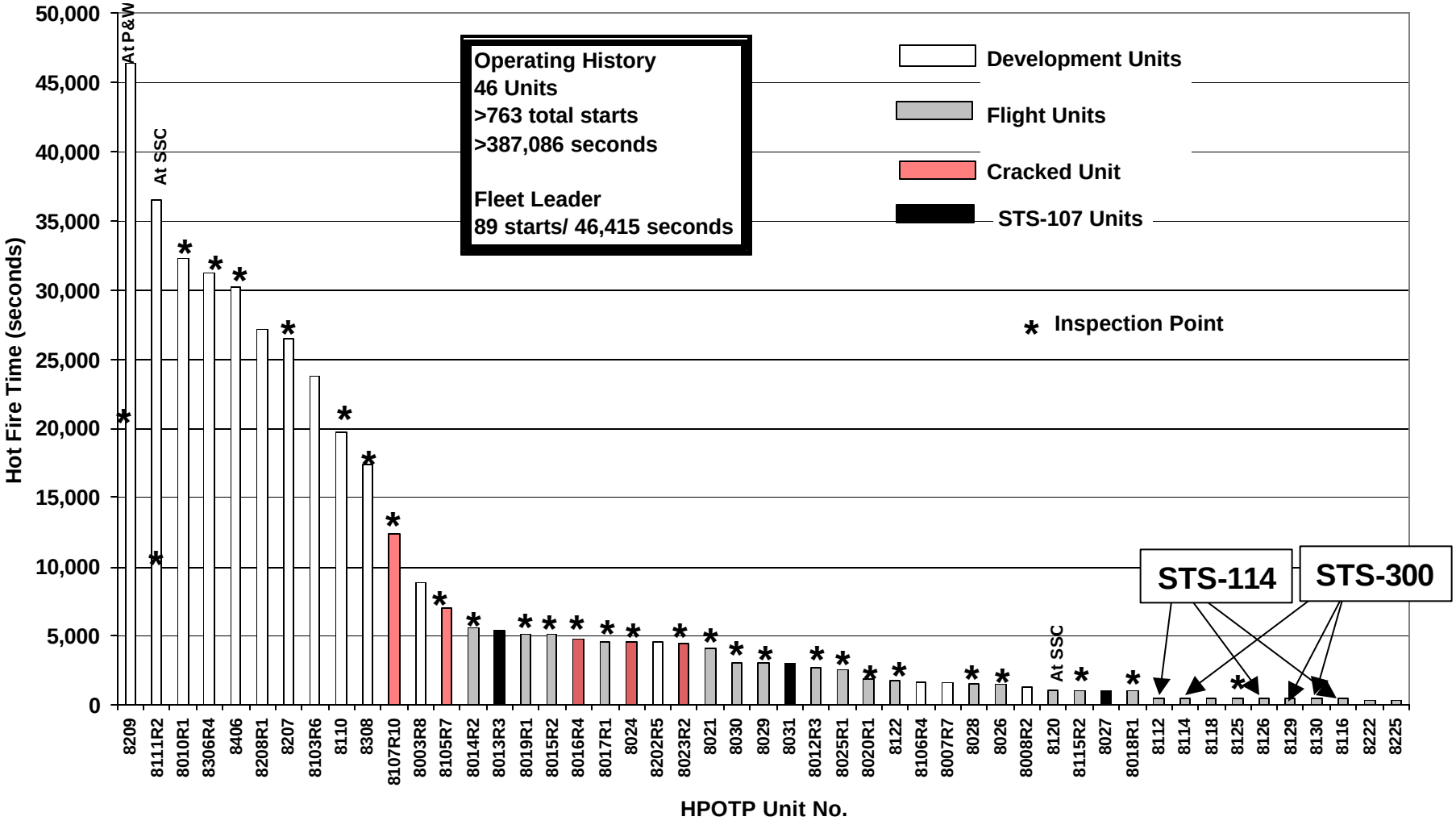


Radial Tooth Crack

One web through crack showing crack growth deceleration

HPOTP Knife Edge Seal

Outboard Seal (-011) Cracking



STS-114 units very low time relative to demonstrated experience with cracking

HPOTP Knife Edge Seal

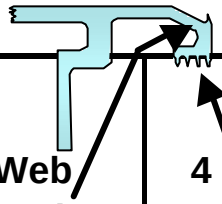
Outboard Seal (-011) Cracking

- **Investigation / Analysis**
  - Materials analysis indicates high cycle fatigue failure mechanism
    - High dynamic vibratory load / flutter
    - Supported by analysis, flutter rig, and hot fire testing
  - Single occurrence of web cracking correlated to assembly error and unique operating conditions
- **Sustaining Flight Mitigation Actions**
  - Assembly build clearance verification
  - Green run data review to screen for flutter response frequencies
  - Implement life limit / inspection requirement to maintain margin on demonstrated experience
    - 50% / 25% of lowest time cracked unit

HPOTP Knife Edge Seal

Flight Seal Inspection History / Life Limitation

DAR Limiting Unit



HPOTP	Starts	Seconds	Web Cracks	4 Tooth Cracks
8014R2	11	5644	*No*	*No*
8019R1	10	5155	*No*	*No*
8015R2	11	5154	*No*	*No*
8016R4	10	4821	**Yes**	**Yes**
8017R1	9	4633	*No*	*No*
8024	9	4608	*No*	**Yes**
8023R2	9	4457	*No*	**Yes**
8021	9	4141	*No*	*No*
8030	6	3083	*No*	*No*
8029	6	3081	*No*	*No*
8012R3	6	2716	*No*	*No*
8025R1	5	2571	*No*	*No*
8020R1	4	1907	*No*	*No*
8122	4	1811	*No*	*No*
8028	3	1548	*No*	*No*
8026	3	1537	*No*	*No*
8115R1	2	1039	*No*	*No*
8018R1	2	1035	*No*	*No*

Inspection Limit

Life Limitation

DAR PW0311R1

- Life = 2228 seconds
  50% of unit 8023R2
  - earliest evidence of teeth cracking
- Inspection @ 1114 seconds*
  25% of unit 8023R2

*Level II waiver to allow exceedance of inspection interval in event of RTLS abort

HPOTP Knife Edge Seal

Outboard Seal (-011) Cracking

- **Rationale for Flight**
  - All flight HPOTPs retrofit with new seals
  - Seal clearances verified to be within family
  - No evidence of flutter frequency during green runs
  - Life limit and inspection interval provides margin against seal failure (loss of material)
    - No occurrence in program history
  - Demonstrated hot fire operation with seal cracking (5 units) to a minimum of 4457 seconds
    - DAR PW0311R1 allows maximum of 1274 seconds (with waiver) prior to inspection

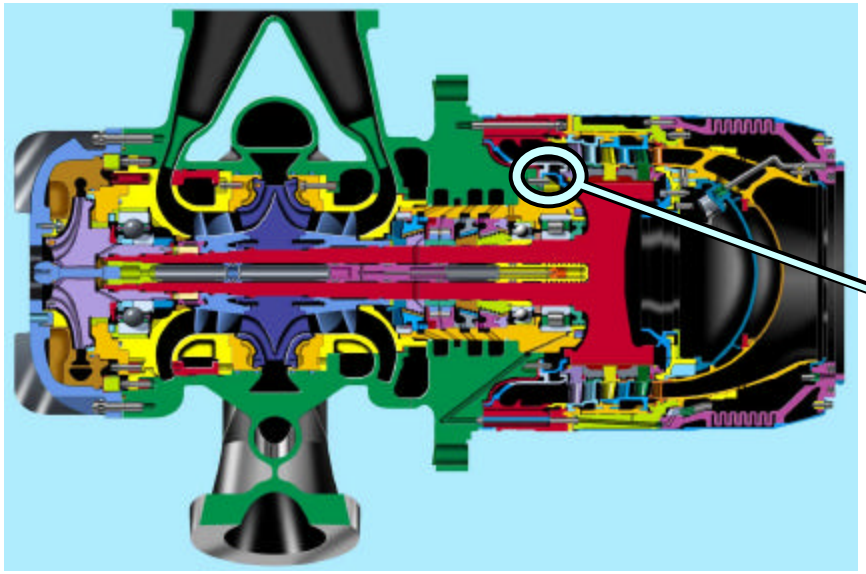
HPOTP Knife Edge Seal

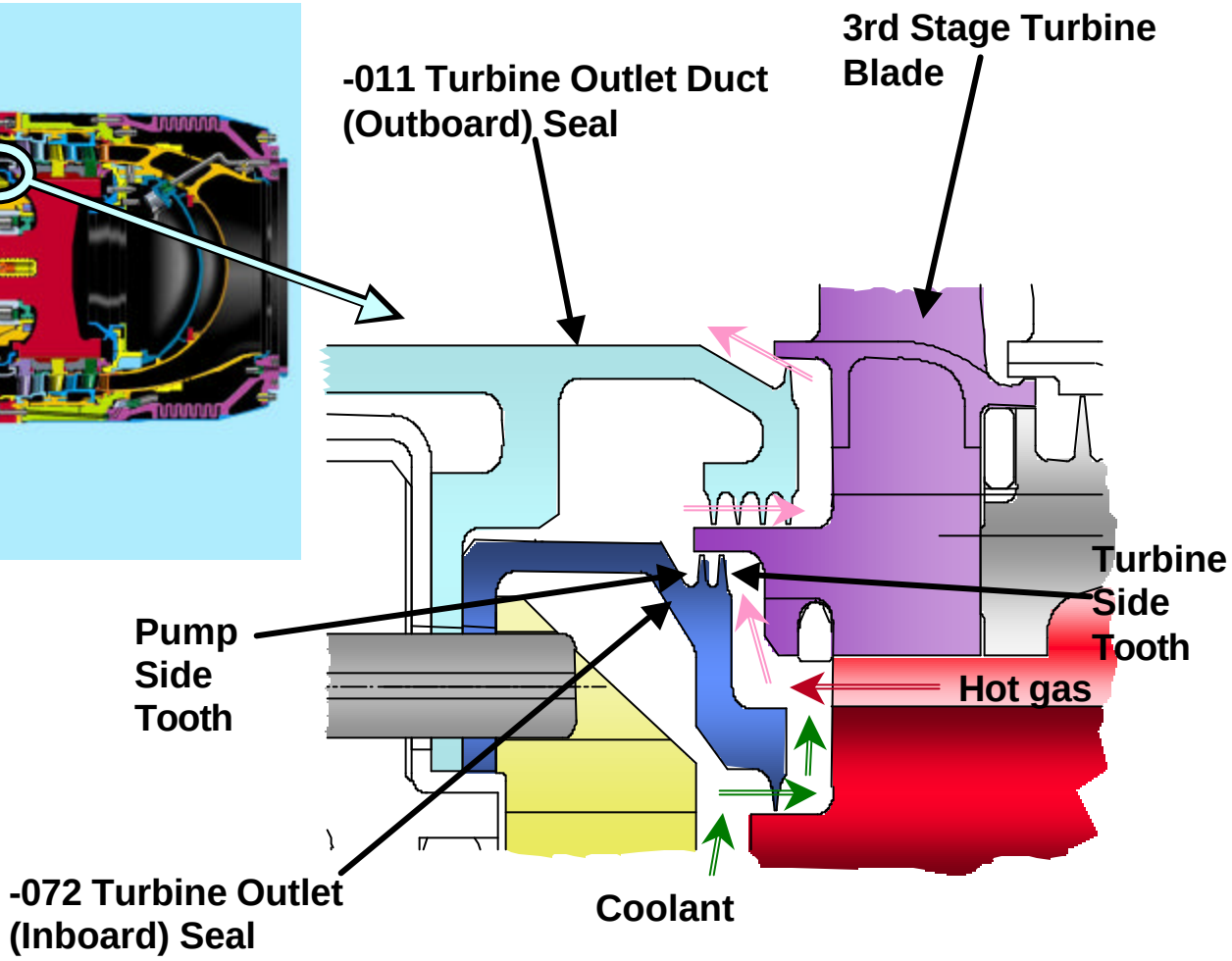
Inboard Seal (-072) Cracking

- **Issue**
  - Loss of Turbine Inboard Seal knife edge creates FOD concerns to downstream components
  - Loss of both knife edge teeth could impact stability of outboard (-011) seal resulting in cracking and downstream FOD concerns
- **Background**
  - Cracks and material loss found in knife edge 2-tooth seal during scheduled overhaul of 5 flight HPOTPs
    - Pump side tooth cracking and material loss on 4 of 5 seals
    - 3 of 5 had turbine side tooth cracking also (no material loss)
    - Pump side tooth cracking only (no material loss) on one seal
  - Cracking and material loss had no significant impact on seal functionality or engine operation

HPOTP Knife Edge Seal

Inboard Seal (-072) Cracking

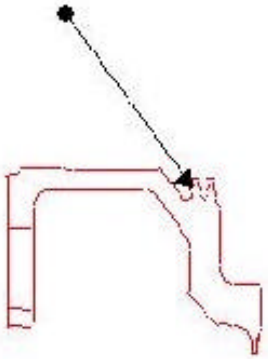


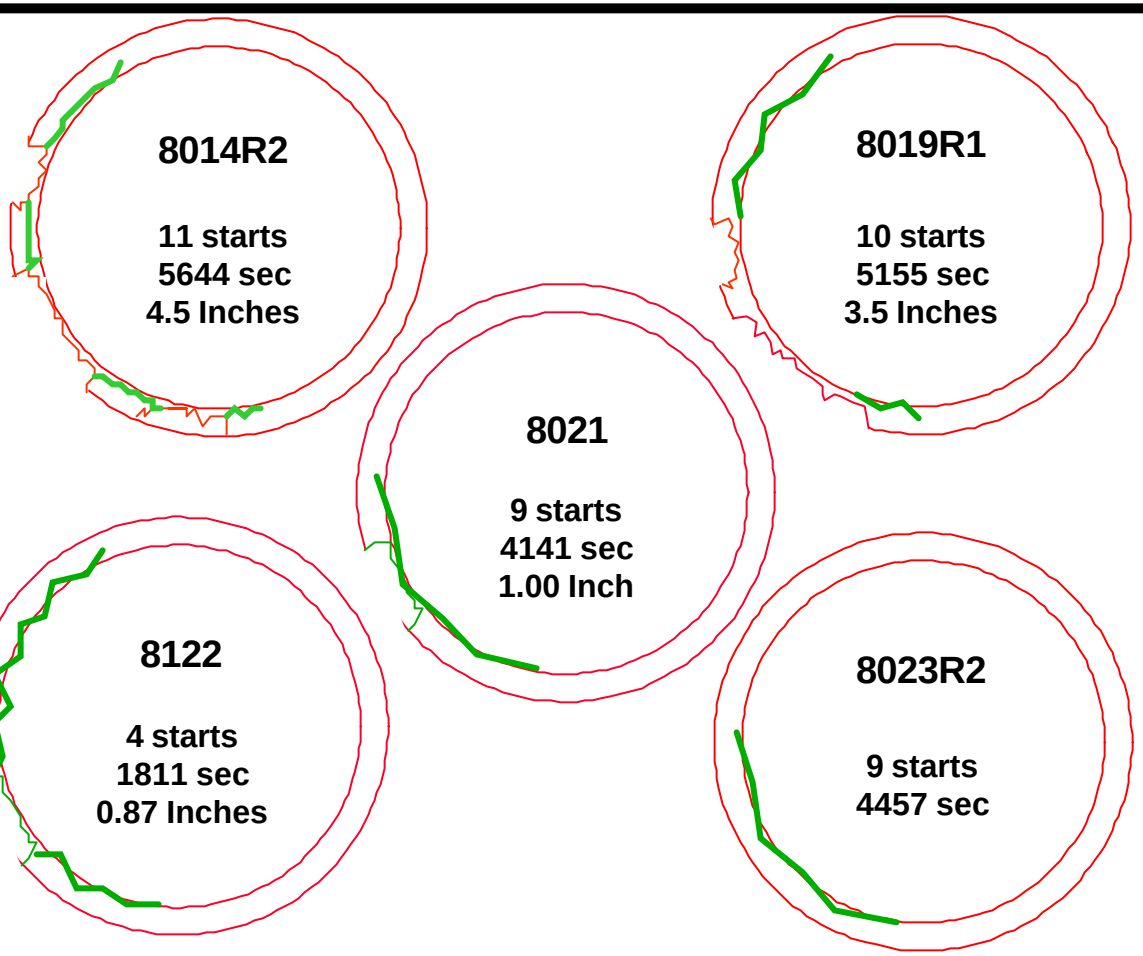


HPOTP Knife Edge Seal

-072 Seal Pump Side Tooth Crack Map

Area of Indications





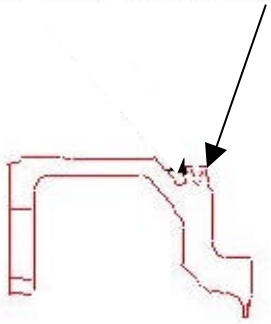
Crack Region

Crack patterns show loss of entire tooth is unlikely

HPOTP Knife Edge Seal

-072 Seal Turbine Side Tooth Crack Map

Area of Indications



Crack Regions

8014R2

11 starts

5644 sec

Surface cracks only observed after sectioning for fractography of pump side tooth

8019R1

10 starts
5155 sec

8021

9 starts
4141 sec

8122

4 starts

1811 sec

No Cracks

8023R2

9 starts

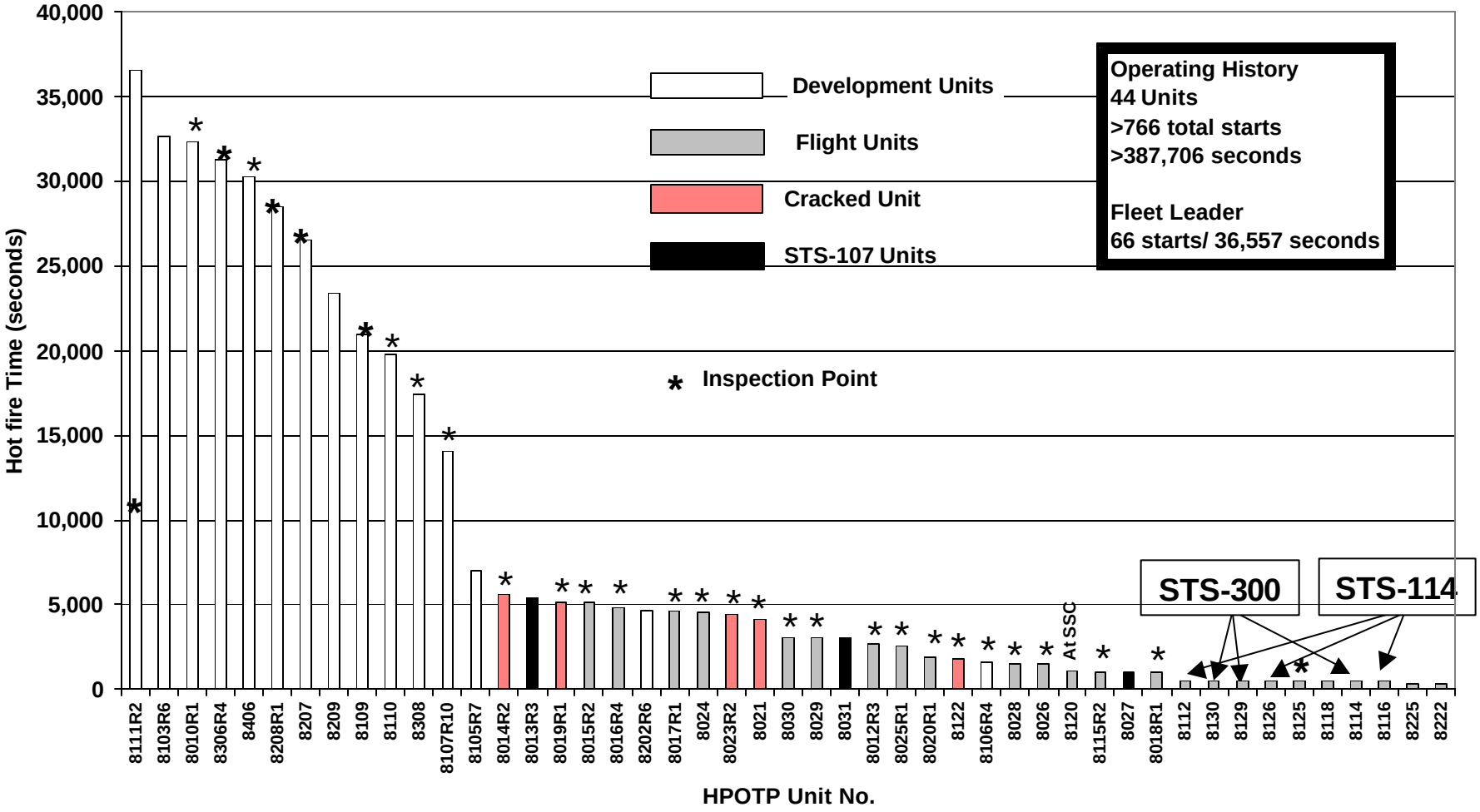
4457 sec

No Cracks

No missing material on turbine side tooth

HPOTP Knife Edge Seal

Inboard Seal (-072) Operational History



STS-114 units very low time relative to demonstrated experience with cracking

HPOTP Knife Edge Seal

Inboard Seal (-072) Cracking

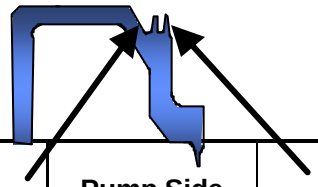
- **Investigation / Analysis**
  - Materials analysis indicates high cycle fatigue failure mechanism
    - High dynamic vibratory load
    - Supported by analysis, laboratory air flow tests, and flutter rig test
  - Pump side only tooth loss has negligible impact on overall seal performance / functionality
  - Significant turbine side tooth loss in combination with pump side tooth loss could impact outboard seal (-011) stability
    - No history of occurrence
  - FOD assessment indicates large margins to catastrophic failure
    - Particle size limited by operational seal clearances
    - > 10 factor to critical HEX impact mass
      - Analysis anchored to ballistic tests

HPOTP Knife Edge Seal

Flight Seal Inspection History / Life Limitation

-072 Inboard Seal

DAR Limiting Unit



HPOTP	Starts	Seconds	Pump Side Tooth Cracks	Pump Side Tooth Missing Pieces	Turbine Side Tooth Cracks	Turbine Side Tooth Missing Pieces
8014R2	11	5644	Yes	Yes	Yes	No
8019R1	10	5155	Yes	Yes	Yes	No
8015R2	11	5154	No	No	No	No
8016R4	10	4821	No	No	No	No
8017R1	9	4633	No	No	No	No
8024	9	4608	No	No	No	No
8023R2	9	4457	Yes	No	No	No
8021	9	4141	Yes	Yes	Yes	No
8030	6	3083	No	No	No	No
8029	6	3081	No	No	No	No
8012R3	6	2716	No	No	No	No
8025R1	5	2571	No	No	No	No
8020R1	4	1907	No	No	No	No
8122	4	1811	Yes	Yes	No	No
8028	3	1548	No	No	No	No
8026	3	1537	No	No	No	No
8115R1	2	1039	No	No	No	No
8018R1	2	1035	No	No	No	No

Inspection Limit

Life Limitation

DAR PW0365R2

- Life = 2070 seconds
  50% of unit 8021
  - earliest evidence of turbine tooth cracks
- Inspection @ 1035 seconds*
  25% of unit 8021

* Level II waiver to allow exceedance of inspection interval in event of RTLS abort

HPOTP Knife Edge Seal

Cracking Inboard Seal (072)

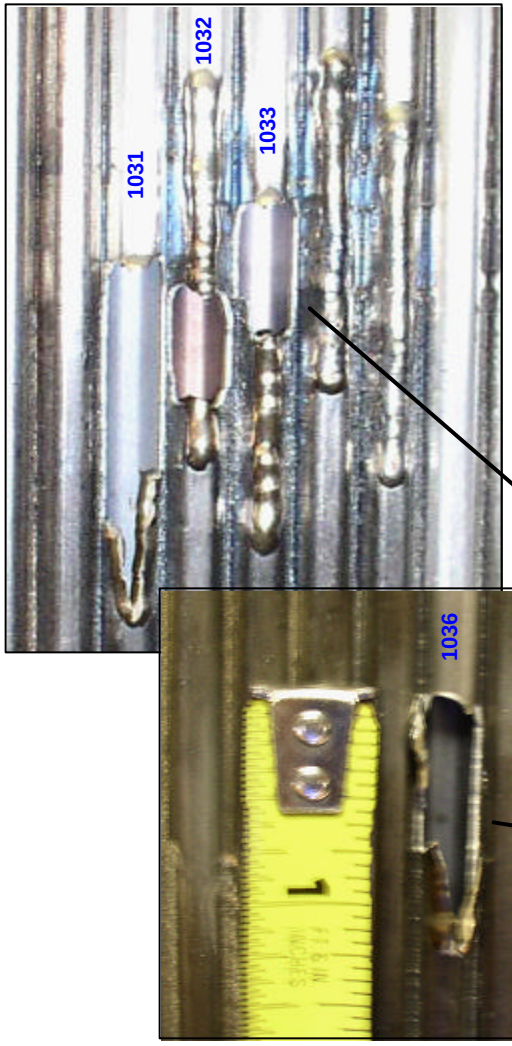
- **Rationale for Flight**
  - All flight HPOTPs retrofit with new seals
  - Large margins to potential FOD damage from pump side tooth failure
  - Life limit and inspection interval provides margin against -072 turbine side tooth failure (loss of material) and -011 seal instability
    - No occurrence in program history
  - Demonstrated hot fire experience with seal cracking (5 units) with times between 1811 and 5644 seconds
    - DAR PW0365R2 allows maximum of 1274 seconds (with waiver) prior to inspection

Nozzle 5007 Tube Ruptures

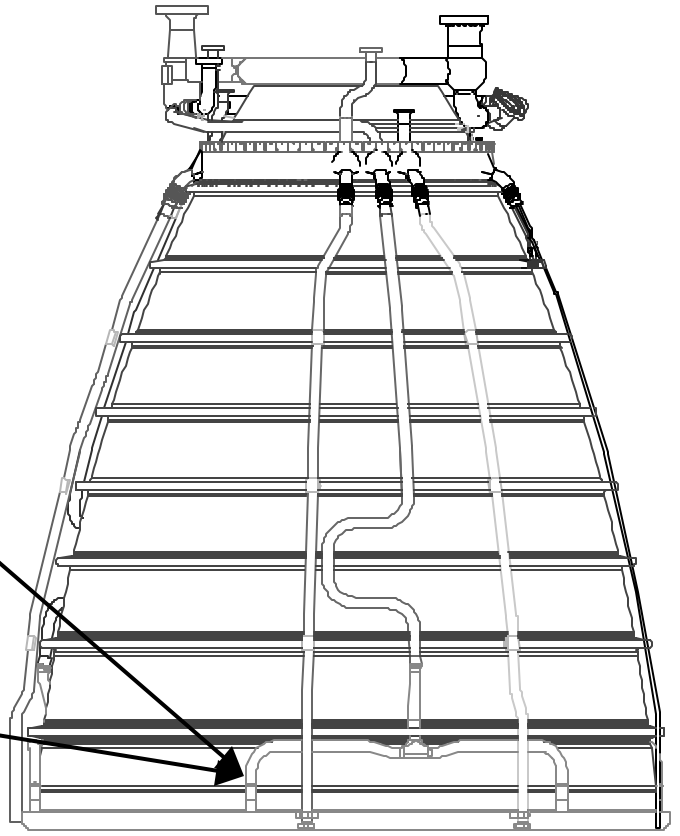
- **Issue**
  - Out of family nozzle tube ruptures discovered during recent acceptance testing at SSC
- **Background**
  - Nozzle 5007 being returned to flight service following factory recycle
    - Aft end Uralite bake-out and forward end tube crown repair
  - Acceptance test 901-983 completed on 17 June at SSC
    - 4 aft end hot wall tubes ruptured during test (prior repaired areas)
      - Three tubes at 2-5 seconds into test
      - Fourth tube approximately 60 seconds into test
    - Test ran full duration (520 seconds) without incident
      - Fuel loss resulted in elevated HPTP discharge temperatures (100 – 180 degrees)
  - Operational History
    - 8 total starts / 4 flights / 4123 seconds

Nozzle 5007 Tube Ruptures

(Tubes 1031, 1032, 1033 and 1036)



- **Tube Ruptures located in the 10th bay**



Nozzle 5007 Tube Ruptures

Investigation Results

- **Fabrication Records Review**
  - No significant processing deviations
- **Operational History**
  - Nominal test and flight history
- **Repair History**
  - Early indications of corrosion leakage
    - Repair required after first hot-fire
      - Post-repair performance “normal”
      - Locations of recent ruptures survived 6 / 7 hot fires
  - Unique forward end tube repair prior to last test
    - No anomalies or leakage post test
  - All tube repairs completed using proven processes and techniques (extensive successful hot fire history)
- **Recycle History**
  - Special 770° F, 5 hour furnace bake performed prior to last hotfire to remove discrepant Uralite near aft manifold

Nozzle 5007 Tube Ruptures

Most Probable Cause

- **Unique thermal processing (Uralite bake-out)**
  - Reduced ductility of braze alloy used in previous tube repairs
    - Confirmed with fractography from N5007 fracture surface
      - Atypical overload fracture through overlay centerline
  - Qualitatively duplicated in the lab with bend tests on exemplar repair specimens
    - “As repaired” fractures highly ductile
    - Brittle, limited ductility fractures following 5 hour simulated furnace bake cycle
      - Comparable discoloration as noted in N5007 fractures (gold vs. typical silver)
  - Quantitative verification with tensile specimens
    - Confirmed 63% reduction in ductility
  - Metallography verified nominal material in N5007
    - A-286 tubes, nickel plating and Nioro braze

Nozzle 5007 Tube Ruptures

- **Preliminary Flight Rationale**
  - Nozzle 5007 tube ruptures caused by unique thermal processing
    - Condition does not exist on STS-114 nozzles
    - Comparable tube repairs on STS-114 nozzles have all completed hotfire with no anomalies

- **Forward Action Plan**
  - Complete fault tree and verify closure of all branches
  - Complete laboratory materials analyses of other potential failure mechanisms (ie. anomalous welding)

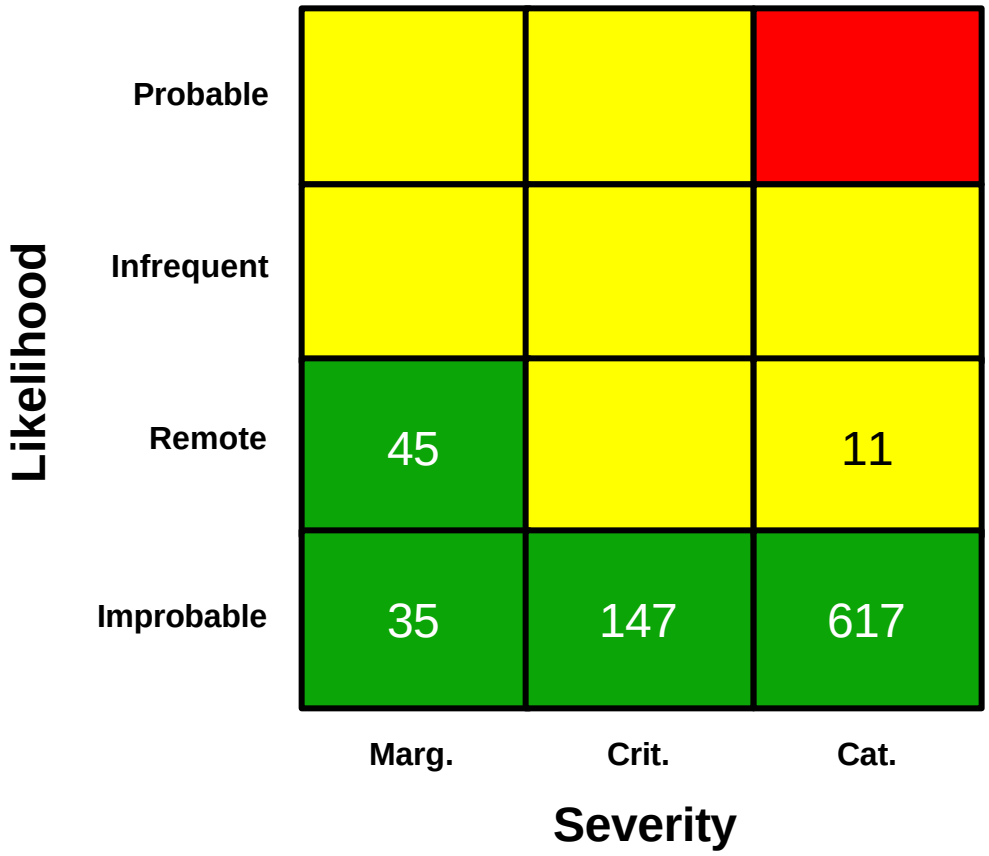
Discovery STS-114

Material Review, Problem Report, and System Notes Reassessment

- **All Material Reviews, Problem Reports, and System Notes (SN) Reassessed**
  - Encompasses entire part / component histories
    - Fabrication
    - Assembly
    - Test
    - Flight
    - Recycle
    - Software
  - Verified proper dispositions in light of current program sensitivities, knowledge and experience
- **All dispositions evaluated and judged acceptable for flight**

SSME Hazard Causes

Risk Matrix



Classification

Unacceptable Risk

Accepted Risk

Controlled Risk

Discovery STS-114

SSME Certification of Flight Readiness

- **CoFR Exceptions**
  - None

Atlantis STS-300

Engine Status

STS-300 Engines: ME1-2051 ME2-2048 ME3-2045

Engines are installed in the vehicle

All current flight and ground test anomalies have been evaluated with respect to impact on Atlantis main engines

Engines are ready, except for routine flow processing

Discovery STS-114

SSME Readiness Statement

- **The Discovery Main Engines are in a ready condition for STS-114 pending closure of open items**

A.E. Goldman
Manager
SSME Project

J. S. Paulsen
Program Manager
Space Shuttle Main Engine